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DESIGN OF WATER-DRIP COOLING FACILITIES FOR HEAT TREATMENT OF MILL ROLLERS

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Water-drip cooling devices based on centrifugal jet atomizers are studied experimentally. Their main operating characteristics such as the irrigation density, the uniformity of the distribution of irrigation over the cooled surface, the dependence of the heat transfer factor on the surface temperature, etc. are determined. The effect of the design and production parameters of the quenching facilities on their operating characteristics and mode of cooling of large steel articles is considered for mill rollers as an example. The results of the tests are used to design cooling facilities and heat treatment processes for mill rollers with the use of water-drip quenching.

Key words: heat treatment, water drip cooling, centrifugal jet atomizers, density of irrigation, heat transfer factor, structural transformations, mill rollers.

INTRODUCTION

The quality of mill rollers should always be high because it determines the rolling rate and the quality of the rolled products obtained. The rollers operate under rigid conditions of high rolling rates and reduction ratios. To raise the operating stability of rollers they should posses sufficient hardenability for formation of required thickness of the active layer with required hardness level. Another important characteristic in addition to the appropriate hardened layer is the level of residual stresses [1]. An optimum combination of these properties is hard to provide by traditional heat treatment modes; normalizing provides a low level of residual stresses at a low thickness of the hardened layer, quenching in liquid environments and hardening by high-frequency currents provides the required strength characteristics but the residual stresses in the rollers are enhanced, which may cause failure of the articles prior to the start of their operation [2 – 4].

This problem can be solved by the use of water drip cooling in quenching after three-dimensional heating. The cooling conditions required for formation of a specified structure in the material of a roller and of the needed combination of properties on the whole can be obtained by varying the design and process parameters of the quenching facility (arrangement of the atomizers in the cooling device, water pressure, distance from the atomizers to the cooled surface) [5 – 8].

Despite the obvious advantages the possibility of application of water drip cooling for heat treatment of large articles has not been studied enough.

The aim of the present work was to design an advanced cooling device for heat hardening of mill rollers on the basis of an experimental study of the special features of operation of water drip quenching devices and numerical simulation of the process of cooling of rollers.

METHODS OF STUDY

We used centrifugal jet atomizers for water drip quenching of mill rollers [9, 10]. An atomizer consisted of a cylindrical insert with three through openings (two peripheral openings located in one line at equal distances from the central opening) and a nozzle with a conical chamber for stirring swirling flows of water. The water flows swirled because the peripheral openings in the insert were drilled at an angle to the axis of the central opening. The integral water flow was 350 – 800 liters/h. The varied design parameters of the atomizers were the diameters of the nozzle mouth (3.0 – 5.0 mm), of the central opening of the insert (1.8 – 2.7 mm) and of the peripheral openings of the insert (2.0 – 2.9 mm). The tests were performed at a water pressure of 300 kPa and a distance from the nozzle of the atomizer to the cooled surface equal to 0.3 m.

The hydraulic characteristics of the cooling devices were studied in a special laboratory facility [1] that allowed us to control the changes both in the distance between the atomizers in the cooling device (L = 0.15 – 0.25 m) and in the dis-

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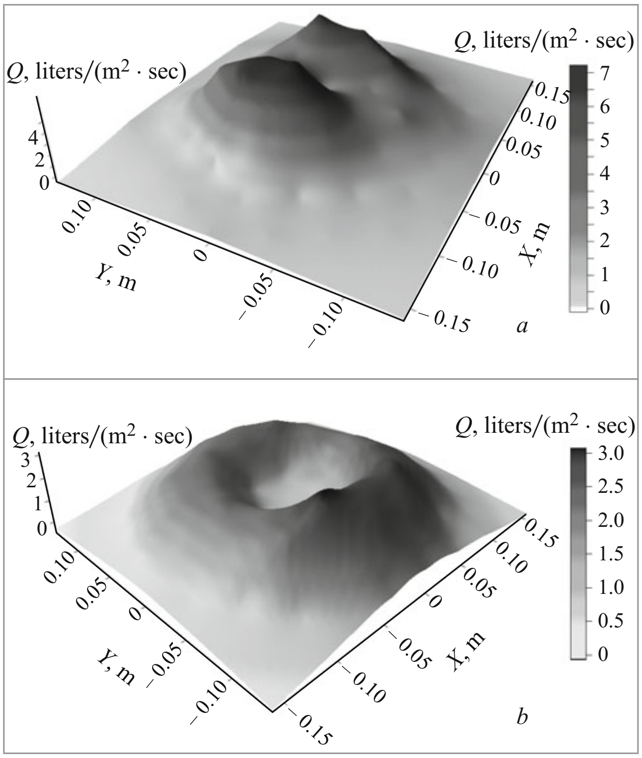

Fig. 1. Three-dimensional distribution of the density of irrigation Q for centrifugal jet atomizers with nozzle diameter 3.5 mm (*a*) and 3.0 mm (*b*) at a water pressure of 300 kPa and a distance from the atomizer to the cooled surface of 0.3 m.

tance from the atomizers to the cooled surface (H = 0.25 – 0.45 m).

The cooling capacity of the quenching devices was determined with the help of a thermal probe in the form of a plate from austenitic steel 12Kh18N10T $250 \times 200 \times 3$ mm in size, which was thermally insulated on one side. An XA thermocouple was welded to the plate and used to detect the variation of the temperature during cooling. The temperature of heating of the thermal probe in the laboratory furnace was 850 ± 10°C.

Pearlitic transformation in steel rollers under water drip quenching was simulated numerically with the help of a method of prediction of structural transformations at a specified cooling law [4]. The initial data for the computation were isothermal diagrams of decomposition of supercooled austenite in steels 50KhN, 9KhF and 45Kh5MF [12] and dependences of the heat transfer coefficient on the temperature determined experimentally under laboratory conditions.

We studied a number of centrifugal atomizers with water flows of 350 – 800 liters/h in order to determine optimum design parameters for service in the cooling device for mill rollers. The tests allowed us to determine the main hydraulic characteristics of the atomizers, namely, the laws of distribution of the irrigation density over the cooled surface, the mean density of the irrigation Q, and its standard deviation S_Q characterizing the uniformity of the atomization.

RESULTS AND DISCUSSION

Our tests show that the changes in the design parameters of the atomizer affect substantially the form of the spray (Fig. 1). For example, a 15% decrease in the nozzle diameter (from 3.5 to 3.0 mm) lowers the value of S_Q by 25%, which is accompanied by substantial widening of the spray diameter (from 0.20 to 0.28 m, i.e., by 40%). On the whole, growth in the diameter of the nozzle and in the diameters of the openings in the insert of the atomizer in the ranges studied doubles the value of Q [from 1.5 to 3.0 liters/(m^2 · sec)] and increases the value of S_Q by a factor of 4 [from 0.75 to 3.0 liters/(m^2 · sec)].

Basing ourselves on the results obtained we chose an atomizer with the following design parameters: the diameter of the nozzle opening 3.0 mm, the diameter of the central opening of the insert 1.8 mm, the diameter of the peripheral openings of the insert 2.1 mm. Such an atomizer has a satisfactory “pan” shape of the spray with a minimum drop of the irrigation density as compared to the other studied atomizers [S_Q = 0.75 liters/(m^2 · sec) at Q = 1.50 liters/(m^2 · sec), Fig. 1*b*], which is the most suitable variant for operation of a group of several atomizers in the quenching device.

We suggest that mill rollers should be quenched in a horizontal water drip cooling device in the form of a cylindrical body with several parallel manifolds with atomizers. The atomizers on neighbor manifolds are arranged in a chess order to provide the highest uniformity of the irrigation. To determine the optimum distance between the atomizers we simulated the operation of the cooling device at a laboratory. The simulated object was an “elementary cell” of the cooling device, i.e., three neighbor atomizers placed at the vertexes of an equilateral triangle with a side equal to L. As a result of regression analysis of the experimental data we obtained the following analytical equations relating the mean density of irrigation Q and its standard deviation S_Q to the parameters of the quenching device, i.e.,

$$Q = 4.28 - 3.79H - 2.97L, \quad (1)$$

$$S_Q = 1.74 - 3.36H + 1.74L. \quad (2)$$

The coefficient of multiple correlation for Eq. (1) is 0.98; for Eq. (2) it is 0.97. The ratio of the tabulated Fisher’s criterion to the computed one is 142 and 72 respectively at a confidence probability of 0.95, which reflects high adequacy of the models obtained.

Analysis of Eqs. (1) and (2) shows that growth in the distance H from 0.25 to 0.45 m (at L = 0.20 m) decreases Q by 26% [from 2.7 to 2.0 liters/(m^2 · sec)]. Then S_Q decreases by 54% [from 1.3 to 0.6 liters/(m^2 · sec). When the distance L is increased from 0.15 to 0.25 m (at H = 0.3 m), Q decreases by 14% [from 2.7 to 2.3 liters/(m^2 · sec) and S_Q increases by 20% [from 1.0 to 1.2 liters/(m^2 · sec)]. Thus, in accordance with equation (2), the highest uniformity of the distribution of the irrigation density over the cooled surface is attained at

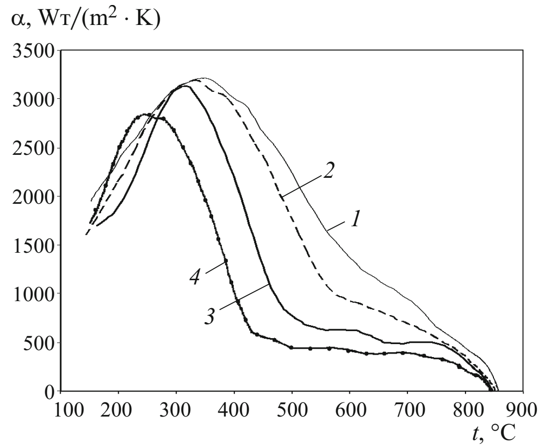

Fig. 2. Temperature dependences of the heat transfer factor α of the water drip quenching device at distance $L = 0.15$ m between the atomizers and distance h from the atomizers to the cooled surface equal to: *1*) 0.25 m; *2*) 0.30 m; *3*) 0.35 m; *4*) 0.45 m.

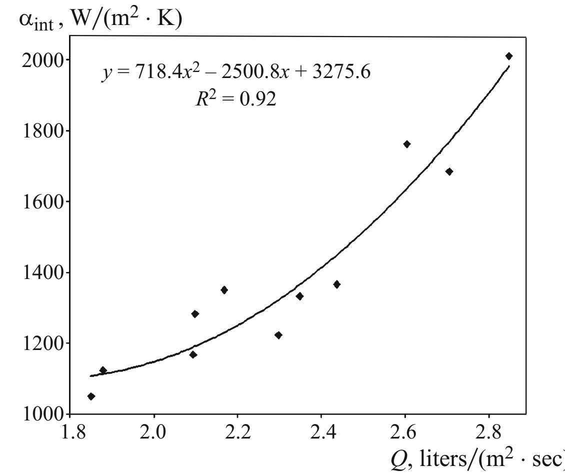

Fig. 3. Mean integral heat transfer factor α_{int} as a function of the mean irrigation density Q of the water drip quenching device.

distance H no less that 0.45 m [in this case $S_Q = 0.48$ liters/(m^2 · sec)] at $L = 0.15$ m.

However, it is known [9, 13] that when the distance between the atomizers and the cooled surface is too long, the irrigation density lowers, which decreases the intensity of the heat transfer and, as a consequence, reduces the thickness of the hardened layer of the roller. We see that the arrangement of atomizers in the quenching device can be optimized for obtaining the most uniform distribution of the irrigation at the required density by joint solution of Eqs. (1) and (2). Such computations gave us the following parameters of the quenching device: $H = 0.3$ m and $L = 0.15$ m. According to Eqs. (1) and (2) such design of the quenching device should give $Q = 2.7$ liters/(m^2 · sec) and $S_Q = 0.99$ liters/(m^2 · sec).

To simulate numerically the structural transformations in mill rollers due to their cooling in the water drip quenching device we should know the cooling capacity of the device and the effect of the design parameters (H, L) on this quantity. The cooling capacity of the quenching device is characterized by the temperature dependence of the heat transfer factor, which is computed by the formula [14]

$$\alpha = \frac{c\rho\,\delta\,v_{cool}}{t - t_w}, \tag{3}$$

where α is the heat transfer factor, W/(m^2 · K); c is the specific heat capacity of the cooled metal, J/(kg · K); ρ is the density of the steel, kg/m^2; δ is the distance from the cooled surface to the hot junction of the thermocouple, m; v_{cool} is the cooling speed at the given moment of time, K/sec; t is the temperature at the given moment of time, °C; and t_w is the temperature of the cooling water, °C.

Figure 2 presents the heat transfer factor α as a function of the surface temperature at $H = 0.25 – 0.45$ m and $L = 0.15$ m. It can be seen that when H grows from 0.25 to 0.45 m, the heat transfer factor decreases in the whole of the temperature range, and the peak of the cooling intensity shifts toward lower temperatures. The decrease in the heat transfer factor upon increase in the distance H is connected with lowering of the kinetic energy of the drops falling to the cooled surface and of the mean density of the irrigation, which has also been noted in [15]. This promotes growth in the temperature range of stability of the "steam jacket" on the surface of the cooled article, which shifts the peak of the cooling intensity typical for bubble boiling toward lower temperatures [16]. It has been shown that a change in the distance L between the atomizers at the same distance from the atomizers to the cooled surface H affects the behavior of the dependence of the heat transfer factor on the temperature inconsiderably.

The obtained dependences of the heat transfer factor on the temperature allowed us to compute the mean integral heat transfer factor in the range of cooling temperatures for various combinations of parameters of the quenching device. This allowed us to derive an analytical equation of the following form with the help of regression analysis:

$$\alpha_{int} = 3240 - 3610H - 2560L, \tag{4}$$

where α_{int} is the mean integral heat transfer factor, W/(m^2 · K); H is the distance to the cooled surface, m; and L is the distance between the atomizers, m.

Analysis of equation (4) shows that growth in the distance H by a factor of 1.8 (from 0.25 to 0.45 m at $L = 0.15$ m) decreases α_{int} by 37%, i.e., from 1950 to 1235 W/(m^2 · K). When the value of L is increased by a factor of 1.7 (from 0.15 to 0.25 m at $H = 0.25$ m), the value of α_{int} decreases by 13%.

Joint analysis of experimental data obtained in hydraulic and thermal engineering studies of the water drip quenching device allowed us to determine the dependence of coefficient α_{int} on the mean density of irrigation of the cooled surface Q (Fig. 3). This dependence has a parabolic form and shows

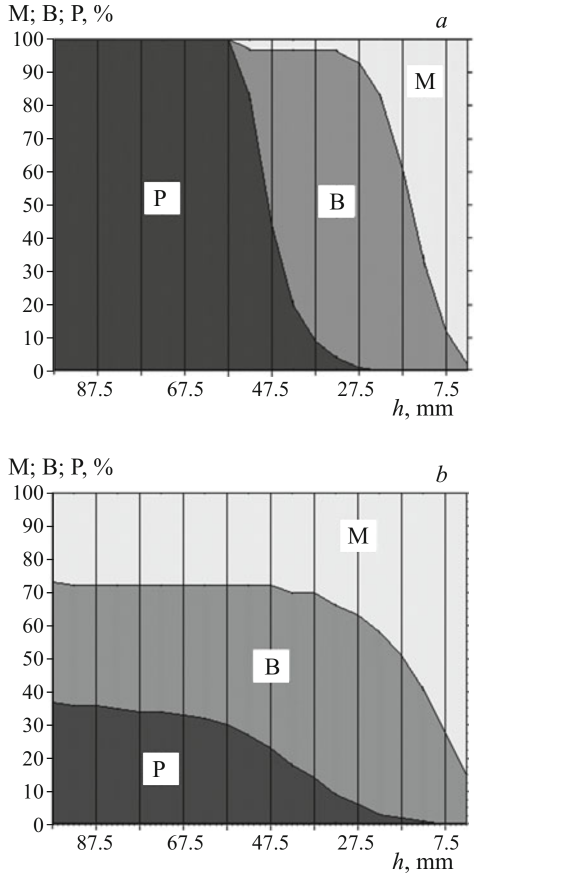

Fig. 4. Distribution of structural components over cross section of rollers 0.2 m in diameter from steels 9KhF (*a*) and 50 KhN (*b*) at distance $h = 0.25$ mm from the atomizers to the cooled surface and distance $L = 0.15$ m between the atomizers: h) distance from the surface to the center of the roller over a radius; M) martensite; B) bainite; P) pearlite.

that when Q is increased from 1.8 to 2.9 liters/(m^2 · sec), the coefficient α_{int} grows from 1100 to 2000 W/(m^2 · K). It can be seen that the problem of determining the desired parameters for the quenching device can be solved. Knowing the intensity of the irrigation required for obtaining the necessary properties and structure in the article we can determine the corresponding irrigation density and the main process parameters of the quenching device, i.e., the distance to the cooled surface and the distance between the atomizers in the device. Since the stability of supercooled austenite in steels with different chemical compositions differs, we should know exactly the intensity of cooling of a roller with specified diameter from the steel of the specified grade for formation of a hardened layer with the required thickness. It is impossible to determine such a dependence for every grade of roll steel because this is too time- and material-consuming. It is expedient to resort to computer simulation of cooling of rolls of various diameters from various steels in the water drip quenching device and to estimate the effect of the cooling conditions on formation of the active layer.

We have computed the distribution of structural components due to cooling of rollers 0.2, 0.6 and 1.0 m in diameter in a water drip device with the distance from the atomizers to the surface of the roller barrel $H = 0.25$, 0.35 and 0.45 m. The rollers were supposed to be produced from the widely used steels 50KhN, 9KhF and a promising roll steel 45Kh5MF.

Our computations show that the roller with diameter 0.2 m from steel 45Kh5MF has through hardenability at any distance from the atomizers to the cooled surface. The lowest hardenability is exhibited by steel 9KhF. The roller from this steel after water drip cooling at $H = 0.35$ m contains up to 15% pearlite even at a distance $h = 2.5$ mm from the surface, wheres the concentration of pearlite in the hardened layer of mill rollers should not exceed 5% [17]. The roller from steel 50KhN with diameter 0.2 m has a hardened layer with a thickness of about 12.5 mm, and the content of martensite in the core amounts to 20% at up to 40% pearlite. At $H = 0.25$ mm the rollers from steels 9KhF and 50KhN have a hardened layer containing over 95% bainite and martensite with a thickness of about 15 – 18 m (Fig. 4).

In the cooled rollers from steels 9KhF and 50KHN with diameter 0.6 m a hardened layer virtually does not form; at the maximum cooling intensity (at $H = 0.25$ m) the content of pearlite at $h = 5$ mm is about 10%. Growth in the distance H to 0.35 m yields up to 60% pearlite in the roller from steel 50KhN already at $h = 5$ mm, while the roller from steel 9KhF contains 100% pearlite over the whole of the cross section. The roller from steel 45Kh5MF with diameter 0.6 m preserves a virtually through hardenability at any distance between the atomizers and the cooled surface of the barrel; the content of martensite in the structure is 85 – 100% over the whole of the cross section, and the content of pearlite does not exceed 5% (Fig. 5*a*).

Cooling of the rollers from steels 9KhF and 50KhN 1.0 mm in diameter produces a chiefly pearlitic structure over the whole of the cross section, while the rollers from steel 45Kh5MF will have a hardened layer with a thickness of 115 – 125 mm (Fig. 5*b*).

Thus, the change in the distance from the atomizers to the cooled surface within 0.25 – 0.45 m for a roller from steel 45Kh5MF does not affect substantially the kind of the distribution of structural components over cross section of the article in contrast to rollers from steels 50KhN and 9KhF. The optimum distance from the atomizers to the cooled surface of rollers from steels 9KhF and 50KhN is $H = 0.25 – 0.30$ m, when the intensity of heat transfer is maximum. On the contrary, in cooling of rollers from steel 45Kh5MF the intensity of heat removal should be lowered, because an enhanced cooling rate in the range of the temperatures of martensitic transformation promotes formation of an elevated level of temporary and residual stresses. In this connection, the distance from the atomizers to the cooled surface of such rollers should be $H = 0.35 – 0.40$ m.

The intensity of heat removal can be lowered by repeated short-term actuation of the atomizers, which lowers substantially the rate of cooling of the barrel.

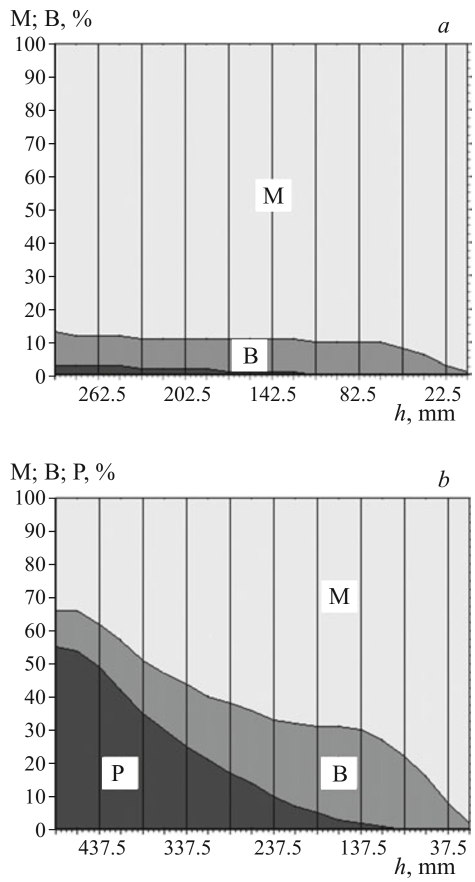

Fig. 5. Distribution of structural components over cross section of the barrel of rollers 0.6 m (*a*) and 1.0 m (*b*) in diameter from steel 45Kh5MF at distances $L = 0.15$ m between the atomizers and $H = 0.45$ m from the atomizers to the cooled surface.

CONCLUSIONS

1. We suggest quenching of mill rollers with the use of water drip centrifugal atomizers with the following optimum design parameters: nozzle opening diameter 3.0 mm, diameter of the central opening of the insert 1.8 mm, diameter of the peripheral openings of the insert 2.1 mm.

2. We suggest a water drip device based on centrifugal jet atomizers for quenching mill rollers with an optimum distance between atomizers $L = 0.15$ m.

3. The dependence of the mean integral heat transfer factor α_{int} on the mean density of irrigation of the cooled surface Q is parabolic; when the value of Q is increased from 1.8 to 2.9 liters/($m^2 \cdot$ sec), the value of factor α_{int} grows from 1100 to 2000 W/($m^2 \cdot$ K).

4. The computations performed show that rollers from steel 45Kh5MF with diameter 0.2 – 0.6 m have through hardenability at any distance between the atomizers and the cooled surface, wheres rollers from steel 9KhF have the lowest hardenability. Cooling of rollers from steels 9KhF and 50KhN with diameter 1.0 mm produces a chiefly pearlitic structure over the whole of the cross section of the rollers. A roller from steel 45Kh5MF with the same diameter has a hardened layer with thickness of 115 – 125 mm.

5. The optimum distance from the atomizers to the cooled barrel surface for rollers from steels 50KhN and 9KhF is 0.25 – 0.30 m, wheres for rollers from steel 45Kh5MF the optimum distance is 0.35 – 40 m.

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